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OPTICALLY PUMPED, SURFACE-EMITTING SEMICONDUCTOR LASER DEVICE AND METHOD FOR ITS MANUFACTURE

The invention concerns an optically pumped surface-emitting semiconductor laser device with at least one radiation-generating quantum well structure and at least one pump radiation source for optically pumping the quantum well structure, in which the pump radiation source comprises an edge-emitting semiconductor structure.

It furthermore concerns a method for the manufacture of such a semiconductor laser device.

A semiconductor laser device of the species initially cited is known from US 5,991,318. An optically pumped vertical resonator semiconductor laser with a monolithic surface-emitting semiconductor layer structure is specified herein. In this known device, the optical pump radiation, whose wavelength is shorter than that of the generated laser emission, is supplied by an edge-emitting semiconductor laser diode. The edge-emitting semiconductor laser diode is externally arranged such that the pump radiation is beamed obliquely from the front into the intensification region of the surface-emitting semiconductor layer structure.

A particular problem with this known device is that the pump laser must be exactly positioned relative to the surface-emitting semiconductor layer structure and, additionally, requires an optical device for beam focusing in order to image the pump radiation exactly into the desired region of the surface-emitting semiconductor layer structure. These measures are associated with considerable technological outlay.

Moreover, in addition to the losses at the optics, coupling losses also occur that reduce the overall efficiency of the system.

A further problem is that only a few quantum wells can be excited by pump radiation due to the pumping from the front.

The object of the present invention is to make available a semiconductor laser device of the type initially cited with simplified adjustment of pump source and surface-emitting layer structure and with high output power. Furthermore, a technically simple method for manufacture of such a device should be specified.

The former object is achieved by an optically pumped, surface-emitting semiconductor laser device with the features of patent claim 1. Advantageous embodiments and developments of the inventive device are the subject matter of subclaims 2 through 18.

Methods for manufacturing inventive semiconductor laser devices are the subject matter of patent claims 26 and 28. Particularly preferred embodiments of these methods are the subject matter of subclaims 27 and 29.

According to the invention, the radiation-generating quantum well structure and the edge-emitting semiconductor structure are epitaxially grown on a common substrate given an optically pumped surface-emitting semiconductor laser device of the type initially cited. The layer thicknesses of the individual semiconductor layers can be very exactly set in the epitaxy, so that a high positioning precision of the edge-emitting semiconductor structure relative to the radiation-generating quantum well structure is advantageously achieved.

Furthermore, with the inventive device a homogenous optical pumping of the quantum well structure can be achieved for high output capacities in the fundamental mode.

In an advantageous embodiment, the surface-emitting quantum well structure and the pump radiation source are arranged side-by-side on the substrate

such that a radiation-emitting region of the pump radiation source and the quantum well structure lie at the same height above the substrate. It is thereby achieved that pump radiation is laterally coupled into the quantum well structure in the operation of the semiconductor laser device. This means that the beam axis of the pump radiation proceeds essentially parallel to the substrate surface and, thus, essentially vertically relative to the beam axis of the laser beam generated by the surface-emitting semiconductor laser device.

Given such a device, the quantum well structure is "pumped" transparently at first from the lateral surfaces in the operation until, finally, its entire lateral cross-sectional area is laser active. Due to the lateral optical pumping, moreover, a uniform filling of the quantum wells with charge carriers is achieved.

Preferably, the quantum well structure is surrounded by the edge-emitting semiconductor structure. In this, at least one gain-guided radiation-emitting active region that serves as pump radiation source is formed by means of at least one current injection path on the surface of the semiconductor laser structure. Alternatively, at least one index-guided radiation-emitting active region of the edge-emitting semiconductor structure serves as pump radiation source. This is defined, for example, by means of at least one current injection path on the surface of the edge-emitting semiconductor structure in combination with, for example, etched trenches in the semiconductor structure fashioned along the current injection path.

Preferably, the ends of the current injection paths facing toward the radiation-generating quantum well structure exhibit a spacing of 10 to 50 μm, particularly preferably approximately 30 μm. Disturbing leakage currents and other disturbing influences at the boundary surfaces between the edge-emitting semiconductor structure and the surface-emitting layer sequence, i.e. the nput [sic] surfaces for the pump radiation, are thereby reduced.

The embodiments listed above can be advantageously fabricated overall by means of traditional semiconductor process technology.

When, in the operation of the device, a sufficiently high current flows through the injection paths into the active layer of the pump radiation source, it leads to the formation of intensified spontaneous emission (super-radiation) that is guided into the surface-emitting laser region and are absorbed there. The electron-hole pairs thereby generated are collected in the quantum wells and lead to the inversion in the intensification region of the surface-emitting laser structure.

The excitation of the surface-emitting laser structure can ensue by pumping the quantum well structure or of confinement layers adjacent to this. In the case of pumping the confinement layers, the pump efficiency is preferably increased in that its band gap decreases toward the quantum well structure. This can, for example, be achieved by means of modification of the material composition. Internal electrical fields are thereby generated in the confinement layers that drive the optically generated charg [sic] carriers into the active quantum well region.

In an particularly preferred embodiment, a plurality of pump radiation sources are arranged star-like around the quantum well structure, so that the quantum well structure is transparently "pumped" and laser-active over its entire lateral cross-section in a short time and very homogenously.

The boundary surface between edge-emitting semiconductor structure and quantum well structure is preferably at least partially reflective. It is thereby achieved that a back-reflection into the edge-emitting semiconductor structure results at the edge to the surface-emitting laser region, which leads to the formation of laser radiation in the pump source and therewith to increased pump efficiency.

Generation of laser radiation as pump radiation and therewith increased pump efficiency is alternatively achieved in that, respectively, two pump radiation

sources arranged at opposite sides of the quantum well structure together form a laser structure. The end faces of the edge-emitting radiation sources lying parallel to one another and facing away from the quantum well structure are fashioned as mirror surfaces for this purpose and serve as a resonator mirror. These can, for example, be generated by cleaving and/or etching (for example, dry etching) and can be provided with a passivation layer and/or can be highly reflectively mirrored.

In operation, the opposite pump radiation sources are coupled via the transparently pumped quantum well structure into a single, coherently resonating laser. Given optimum end mirroring, the entire optical power stored in the pump laser is then available as pump power except for the losses at the boundary surfaces between pump laser and surface-emitting laser.

Preferably, the edge-emitting semiconductor structure possesses a large optical cavity (LOC) structure. Given this, an active layer is embedded between a first waveguide layer and a second waveguide layer that are in turn embedded between a first cladding layer and a second cladding layer.

In a particularly preferred development of the semiconductor laser device, the quantum well structure possesses more than 10 quantum wells. This high number of quantum wells is possible because all quantum wells are directly pumped due to the lateral coupling of the pump radiation.

The edge-emitting semiconductor structure of preferably fashioned such that it generates a pump well whose maximum lies at the height of the quantum wells above the substrate, particularly preferable at the height of the center of the quantum well structure.

In order to obtain especially high output powers, in an advantageous development the edge-emitting semiconductor structure is fashioned as what is known as a multiple stack or micro-stack laser with a plurality of laser-active layer

sequences (for example, double heterostructures) that are connected in series via tunnel transitions. The quantum well structure then advantageously comprises a plurality of quantum well groups that respectively lie at the height of a laser-active layer sequence of the pump source.

In a preferred method for manufacturing an optically pumped, surface-emitting semiconductor laser device according to the aforementioned embodiments, a first semiconductor layer sequence suitable for a surface-emitting semiconductor laser and with at least one quantum well structure is initially applied onto a substrate. Subsequently, the first semiconductor layer sequence is removed outside the provided laser region. An edge-emitting, second semiconductor layer sequence is subsequently deposited on the region over the substrate that was uncovered after the removal of the first semiconductor layer sequence, said second semiconductor layer sequence being suitable for generating pump radiation and transmitting it into the quantum well structure. Subsequently, at least one current injection path is fashioned in the edge-emitting semiconductor layer sequence.

Preferably, a buffer layer is first applied onto the substrate. A first confinement layer is deposited thereon. A first confinement layer is first deposited on this. A quantum well structure suitable for a surface-emitting semiconductor laser is subsequently applied onto the first confinement layer and this quantum well structure is followed by a second confinement layer. After the removal of the confinement layers and of the quantum well structure and, partially, of the buffer layer outside the provided surface-emitting laser region, a first cladding layer, a first waveguide layer, an active layer, a second waveguide layer and a second cladding layer are successively applied onto the region of the buffer layer that is then uncovered. The respective layer thicknesses are designed such that the pump radiation generated in the active layer proceeds into the quantum well structure.

In another embodiment of the semiconductor laser device according to the invention, the radiation-emitting quantum well structure and the pump radiation source are arranged above one another on the substrate. The quantum well structure is thereby optically coupled to the edge-emitting semiconductor structure, so that pump radiation from the pump radiation source is guided into the quantum well structure in the operation of the semiconductor laser device.

The edge-emitting semiconductor structure preferably comprises a first waveguide layer and (as viewed from the substrate) a second waveguide layer downstream from this, between which an active layer is arranged. The quantum well structure is epitaxially grown on the second waveguide layer, covers only a sub-region of the edge-emitting semiconductor structure and is optically coupled to this.

To improve the infeed of the pump radiation into the quantum well structure, the boundary surface between second waveguide layer and adjacent cladding layer is bent or buckled toward the quantum well structure in the proximity of the surface-emitting laser region.

In order to improve the infeed of the pump radiation into the surface-emitting semiconductor structure, the refractive index of the second waveguide layer is advantageously higher than the refractive index of the first waveguide layer and/or the active layer is placed asymmetrically in the waveguide fashioned by the two waveguide layers.

Analogous to the above-described first embodiment, one or more gain-guided and/or index-guided, radiation-emitting active regions are preferably fashioned as pump radiation sources in the edge-emitting semiconductor structure.

In a preferred method for manufacturing an optically pumped, surface-emitting semiconductor laser device according to the aforementioned

second basic embodiment and its developments, an edge-emitting semiconductor laser layer sequence is first applied onto a substrate. A surface-emitting semiconductor laser layer sequence with at least one quantum well structure is then applied on this. Subsequently, the surface-emitting semiconductor laser layer sequence is removed outside the intended laser region before at least one current injection path is fashioned in the edge-emitting semiconductor layer sequence.

For this, a buffer layer is preferably first applied onto the substrate. A first waveguide layer, an active layer and a second waveguide layer are subsequently deposited successively on this. A first confinement layer, a surface-emitting semiconductor laser layer sequence with a quantum well structure and a second confinement layer are applied onto the edge-emitting layer sequence thus produced. The confinement layers, the surface-emitting semiconductor laser layer sequence and, in part, the second waveguide layer are then removed outside the intended surface-emitting laser region.

In a preferred development of the two above-recited embodiments, a highly reflective Bragg reflector layer sequence is fashioned at one side of the quantum well structure, said Bragg reflector layer sequence representing a resonator mirror of the surface-emitting laser structure. A further Bragg reflector layer sequence or an external mirror is arranged at the opposite side of the quantum well structure as second, partially transmissive resonator mirror.

Preferably, the substrate is composed of a material that is transmissive for the laser beam generated in the semiconductor laser device, and the highly reflective Bragg reflector is arranged at that side of the quantum well structure facing away from the substrate. This enables a short connection between the semiconductor structures and a heat sink and therewith a good heat dissipation from the semiconductor structures.

In order to prevent disturbing transverse modes (= modes parallel to the substrate - whispering modes), absorber layers are arranged in the edge region and/or in etching structures of the surface-emitting semiconductor laser layer sequence.

The inventive semiconductor laser device is in particular suitable for employment in an external resonator wherein a frequency-selected element and/or a frequency doubler is located.

Via modulation of the pump laser, the inventive semiconductor laser device can be advantageously modulated by modulation of the pump current or via a short-circuit connection of the surface-emitting semiconductor laser layer sequence.

Further advantageous embodiments and developments of the device and of the method according to the invention derive from the exemplary embodiments described in the following in conjunction with Figures 1 through 14.

Shown are:

Figure 1	a schematic representation of a section through a first exemplary embodiment;
Figures 2a through 2e	a schematic representation of a method sequence for manufacturing the exemplary embodiment according to Figure 1;
Figure 3a	a schematic representation of a section through a second exemplary embodiment;

Figure 3b	a schematic representation of an advantageous design of the waveguide of the exemplary embodiment according to Figure 3a;
Figures 4a through 4c	a schematic representation of a method sequence for manufacturing the exemplary embodiment according to Figure 3;
Figure 5	a schematic representation of a plan view onto a first arrangement of current injection paths on an edge-emitting semiconductor structure;
Figure 6	a schematic representation of a plan view onto a second arrangement of current injection paths on an edge-emitting semiconductor structure;
Figure 7	a schematic representation of a plan view onto a third arrangement of current injection paths on an edge-emitting semiconductor structure;
Figures 8a and b	a schematic representation of semiconductor laser devices with absorber layers;
Figure 9	a schematic representation of a modulation-capable semiconductor laser device according to the invention, and
Figure 10	a schematic representation of an inventive semiconductor laser device with an external resonator.

The exemplary embodiment of Figure 1 is, for example, an optically pumped surface-emitting semiconductor laser chip with a laser emission at 1030 nm. In this, a buffer layer 6 is applied on a substrate 1. The substrate 6 is composed, for example, of GaAs and the buffer layer 6 is composed of undoped GaAs.

A surface-emitting semiconductor laser structure 10 having a quantum well structure 11 is applied on the buffer layer 6 centrally over the substrate, this representing the surface-emitting laser region 15. The semiconductor laser structure 10 is composed of a first confinement layer 12 located directly on the buffer layer 6, a quantum well structure 11 arranged on said confinement layer 12, and a second confinement layer 13 applied on the quantum well structure 11.

The confinement layers 12, 13 are composed, for example, of undoped GaAs, and the quantum well structure 11 comprises, for example, a plurality (≥ 3) of quantum wells that are composed of undoped InGaAs whose thickness is set to the emission at 1030 nm and between which barrier layers Of [sic] GaAs are located.

A Bragg mirror 3 with, for example, 28 to 30 periods GaAlAs (10% Al) / GaAlAs (90% Al) that represents a highly reflective resonator mirror is deposited over the surface-emitting semiconductor laser structure.

An edge-emitting semiconductor laser structure 21, for example a known large optical cavity (LOC) single quantum well (SQW) laser structure for an emission at approximately 1 μm, is deposited in the environment of the laser region 15 on the buffer layer 6. This structure 21 is composed, for example, of a first cladding layer 28 (for example, n-$GaAl_{0.65}As$), a first waveguide layer 23 (for example, n-$GaAl_{0.1}As$), an active layer 25 (for example, an undoped InGaAs-SQW), a second waveguide layer 24 (for example, p-$GaAl_{0.1}As$) and a second cladding layer 29 (for example, p-$GaAl_{0.65}As$).

For example, a p^+-doped is [sic] GaAs layer can be applied on the second cladding layer 29 as cover layer 30.

The LOC region 22 is arranged at the same height as the quantum well region of the surface-emitting laser structure 10; preferably, the active layer 25 is located at the same height above the substrate 1 as the quantum well structure 11.

In a particular embodiment of the exemplary embodiment, the edge-emitting semiconductor structure 21 comprises a plurality of active layers 25 that are connected in series via tunnel transitions. Analogous thereto, the quantum well structure 11 comprises a plurality of quantum well groups that respectively lie at the height of an active layer 25 of the edge-emitting semiconductor structure 21.

All semiconductor layers are, for example, produced by means of metalorganic vapor phase epitaxy (MOVPE).

End mirrors 31 proceeding perpendicular to the layers of the edge-emitting semiconductor laser structure 21, said end mirrors 31 extending at least into the first cladding layer 28, here up to the buffer layer 6, proceeding from the cover layer 30, are located in the proximity of the outer edge of the edge-emitting semiconductor laser structure 21. For example, these are produced after the growth of the edge-emitting semiconductor laser structure 21 by means of etching (for example, reactive ion etching) of corresponding trenches and the subsequent filling thereof with highly reflective material. Respectively two mirrors 31 parallel to one another are arranged at opposite sides of the quantum well structure 11 (compare Figures 5 and 6).

Alternatively, the end mirrors can be manufactured in a known manner by cleaving the wafer along crystal planes. As shown in Figure 1, these are then not

necessarily arranged in the chip but are formed by the cloven chip lateral surfaces (compare Figure 7).

An electrically insulating mask layer 7 (for example a silicon nitride, an aluminum oxide or a silicon oxide layer) with which current injection paths 26 of the edge-emitting semiconductor laser structure 21 are defined are located on the free surface of the cover layer 30 and of the Bragg mirror 3 (compare Figures 5 and 6). A p-contact layer 32, for example a known contact metallization, is applied on the mask layer 7 and - in its recesses for the current injection paths 26 - on the cover layer 30.

For example, six stripe arrays with 15 stripes (4μm stripe, 10 μm pitch) with approximately 150μm active width that are arranged symmetrically star-shaped around the surface-emitting laser region 15 are selected for the pump source.

Preferably, the ends of the current injection paths 26 facing toward the radiation-generating quantum well structure 11 exhibit a spacing of 10 to 50 μm, particularly preferably of approximately 30 μm, from said quantum well structure 11. Disturbing leakage currents and other disturbing influences at the boundary surfaces between the edge-emitting semiconductor structure 21 and the surface-emitting layer sequence 10, i.e. at the infeed surfaces for the pump radiation 2, are thereby reduced.

All current injection paths 26 can be provided with a common p-contact layer 32, whereby the radiation-emitting regions of the edge-emitting structure are connected parallel to one another in operation. Given an intended, separate activation of these individual radiation-emitting regions, a correspondingly structured p-conductive first contact layer 32 is applied. An optimized pump light distribution (for example, similar to a Gauss profile) can thereby be generated over the lateral cross-section of the surface-emitting structure.

For generating index-guided pump regions in the edge-emitting structure 21, trenches (manufactured, for example, by etching) can be formed therein along the current injection paths 26 (said trenches not being shown in the Figures), these extending, for example, up to 0.5 μm into the second waveguide layer 24. An improved wave guidance is thereby achieved at the edges of the pump regions.

The principal surface 16 of the substrate 1 facing away from the semiconductor structure is provided with an n-conductive second contact layer 9, for example likewise a known contact metallization, except for an exit window 8 for the laser beam (indicated by the arrow 5).

The principal surface 16 of the substrate is preferably bloomed in the region of the exit window 8 in order to reduce back-reflections into the chip.

A laser resonator of the surface-emitting laser structure 10 can be fashioned from the Bragg mirror 3 and an external, further mirror (not shown in Figure 1) arranged at the opposite side of the substrate 1, or can be formed of a further Bragg mirror arranged between the substrate 1 and the quantum well structure 11.

In the operation of the semiconductor chip, pump radiation (indicated by the arrows 2) is generated in the regions of the edge-emitting semiconductor structure 21 defined by the current injection paths 26 and coupled into the quantum well structure 11 of the surface-emitting laser structure 10.

Given sufficient back-reflection at the boundary surface between edge-emitting [sic] 21 and surface-emitting structure 10 and a suitable position of the end mirrors 31, laser radiation which leads to an increased pump efficiency is generated in the edge-emitting structure 21.

Preferably, the end mirrors 31 are arranged relative to one another such that these form a laser resonator for two radiation-emitting regions of the edge-emitting structure 21 that lie opposite one another. The two radiation-emitting regions lying opposite one another are then coupled to form a single coherently resonating laser after the transparent pumping of the surface-emitting laser structure 10. Given optimal mirroring of the end mirrors 31, the entire optical power generated by the pump laser is available as pump power except for losses at the boundary surface between edge-emitting structure 21 and surface-emitting structure 10.

Given the method schematically shown in Figures 2a through 2e for manufacturing the exemplary embodiment according to Figure 1, the buffer layer 6, the first confinement layer 12, the quantum well structure 11, the second confinement layer 13 and the Bragg mirror layers 3 are initially successively applied onto the substrate 1, for example by means of MOVPE (Figure 2a).

Subsequently, an etching mask 17 (for example, an Si-nitride mask), is applied onto the region of this layer sequence provided as surface-emitting laser region 15. Subsequently, the Bragg mirror layers 3, the confinement layers 12 and 13, the quantum well structure 11 and, in part, the buffer layer 6 are removed (for example by means of etching, for example dry-etching with Cl chemistry) outside the intended surface-emitting laser region 15 (Figure 2b).

The first cladding layer 28, the first waveguide layer 23, the active layer 25, the second waveguide layer 24, the second cladding layer 29 and the cover layer 30 are successively applied on the uncovered region of the buffer layer 6, for example again by means of MOVPE (Figure 2c).

For example, by means of reactive ion etching and suitable known mask technology, trenches for the end mirrors 31 are then etched (see Figure 2d) in the most recently applied edge-emitting structure 21, said trenches being subsequently

coated or filled with reflection-enhancing material. Furthermore, the etching mask 17 we [sic] removed.

Subsequently, the electrically insulating mask layer 7 is applied onto the cover layer 30 and onto the Bragg mirror 3 before the p-contact layer 32 and the n-contact layer 9 are finally produced (Figure 2e).

Before the application of the insulating mask layer 7, the trenches described above in conjunction with Figure 1 for generating index-guided pump lasers, are optionally produced by means of etching.

To reduce radiation losses, the substrate 1 is preferably thinned (for example to less than 100μm) or completely removed after the MOVPE.

In the exemplary embodiment according to Figure 3, initially situated surface-wide on the substrate 1 is [sic] a buffer layer 6 and an edge-emitting semiconductor laser structure 21 wherein an active layer 25 is arranged between a first waveguide layer 23 and a second waveguide layer 24.

In a provided laser region 15 over the middle of the substrate 1, a surface-emitting quantum well structure 11 is grown on the second waveguide layer 24 followed by a confinement layer 13 and a Bragg mirror layer sequence 3.

An electrically insulating mask layer 7 that comprises recesses for current injection paths 26 of the the [sic] edge-emitting structure 21 (compare Figure 7) is applied in the region around the laser region 15 onto the second waveguide layer 24 or, potentially, onto a highly doped cover layer applied thereon. A first contact layer 32 is located on the electrically insulating mask layer 7 and in the recesses thereof on the second semiconductor layer or, respectively, on the cover layer, and a second contact layer 9 with an exit window 8 for the laser beam (indicated by the

arrow 5) is arranged at that side of the substrate 1 lying opposite the first contact layer 32.

To generate index-guided pump regions in the edge-emitting structure 21, trenches manufacetured [sic], for example, by means of etching can be fashioned (not shown in the Figures) in the second waveguide layer 24 along the current injection paths 26. An improved wave guidance at the edges of the pump regions is thereby achieved.

Cleft sides of the chip are, for example, provided here as end mirrors 31 of the edge-emitting structure 21.

In operation, pump laser radiation is generated in the edge-emitting laser structure, of which a part is coupled into the quantum well structure 11 lying above said laser structure.

In order to promote the infeed, the active layer 25 is asymmetrically located in the waveguide formed by the two waveguide layers 23, 24. Alternatively or additionally, for the same purpose the refractive index of the second waveguide layer 24 can be higher than that of the first waveguide layer 23 and/or the second waveguide layer can be pulled up toward the laser region 15 in the direction of the quantum well structure 11 (compare Figure 3b).

Materials listed for the corresponding layers of the exemplary embodiment according to Fig. 1 can be used by way of example here as materials for the various layers.

A laser resonator of the surface-emitting laser structure 10 can also be formed in this exemplary embodiment from the Bragg mirror 3 and from an external further mirror (not shown in Figure 3a) arranged at the opposite side of the

substrate 1 or a further Bragg mirror arranged between the substrate 1 and the quantum well structure 11.

Given the method for manufacturing a device according to the exemplary embodiment of Figure 3a that is schematically shown in Figures 4a through 4c, a buffer layer 6 is first applied onto the substrate 1. The first waveguide layer 23, the active layer 25 and the second waveguide layer 24 are subsequently successively grown on this. Subsequently, the quantum well structure 11 is grown onto the second waveguide layer 24, followed by the confinement layer 13 and the Bragg mirror layer 3 (Figure 4a). These layers are produced, for example, by means of MOVPE.

Subsequently, an etching mask 17 is applied onto the sub-region of the grown layer sequence that is provided as laser region 15, and the Bragg mirror layer 3, the confinement layer 13, the quantum well structure 11 and, in part, the second waveguide layer 24 are removed outside the laser region 15 by means of etching (Figure 4b).

Subsequently, for definition of the current injection paths 26, the electrically insulating mask layer 7 is applied onto the second waveguide layer 24 before the contact layer 32 is then deposited.

Subsequently, the second contact layer 9 with an exit window 8 is applied onto the principal surface of the substrate 1 lying opposite the semiconductor layer sequence (Figure 4c).

To reduce radiation losses, the substrate 1 here is also preferably thinned (for example to less then 100μm) or is completely removed after the MOVPE.

The inventive (what are known as) wafer lasers are preferably soldered with the Bragg mirror down onto a heat sink. One electrode is located on the heat sink; the second is generated by bonding on the wafer laser surface.

In order to prevent disturbing transverse modes (= modes parallel to the substrate - whispering modes), absorber layers 18 (compare Figures 8a and 8b) are arranged in the edge region and/or in etched structures of the surface-emitting semiconductor laser layer sequence 15. Suitable absorber materials for such applications are known and are therefore not explained in greater detail at this point.

The inventive semiconductor laser device is in particular suited for employment in an external resonator with an external mirror 33 and a partially transmissive concave reflection mirror 34 in which a frequency-selected element 35 and/or a frequency doubler 36 is located (compare Figure 9).

Advantageously, the inventive semiconductor laser device can then be modulated via modulation of the pump source (by modulating the pump current) or via a short-circuit connection of the surface-emitting semiconductor laser layer sequence (compare Figure 10).

The above-described structures can be employed not only in the InGaAlAs system employed by way of example but, for example, can also be employed in the InGaN, InGaAsP or in the InGaAlP system.

Given a wafer laser in the InGaN system for an emission at 470 nm, the quantum wells are composed, for example, of InGaN for 450 nm emission, the confinement layers are composed of InGaN with reduced refractive index, and the Bragg mirrors are composed of an InGaAlN system. The pump laser structure comprises an active region with quantum wells of InGaN for emission at

approximately 400 nm as well as waveguide layers and cladding layers of GaAlN, wherein the desired refractive indices are set by variation of the Al content.

Patent Claims

1. Optically pumped surface-emitting semiconductor laser device with at least one radiation-generating quantum well structure (11) and at least one pump radiation source (20) for optically pumping the quantum well structure (11), in which the pump radiation source (20) comprises an edge-emitting semiconductor structure (21),
characterized in that
the radiation-generating quantum well structure (11) and the edge-emitting semiconductor structure (21) are epitaxially grown on a common substrate (1).

2. Semiconductor laser device according to claim 1,
characterized in that
the radiation-emitting quantum well structure (11) and the pump radiation source (20) are arranged side-by-side such that a radiation-emitting region (22) of the pump radiation source (20) and the quantum well structure (11) lie at the same height above the substrate (1), so that pump radiation (2) is laterally coupled into the quantum well structure (11) in the operation of the semiconductor laser device.

3. Semiconductor laser device according to claim 2,
characterized in that
the quantum well structure (11) is surrounded by the edge-emitting semiconductor structure (21) wherein at least one gain-guided radiation-emitting active region that serves as pump radiation source (20) is formed by means of at least one current injection path (26) on the surface of the semiconductor laser structure (21).

4. Semiconductor laser device according to claim 2,
characterized in that

the quantum well structure (11) is surrounded by the edge-emitting semiconductor structure (21) wherein at least one index-guided radiation-emitting active region that serves as pump radiation source (20) is defined by means of at least one current injection path (26) on the surface of the semiconductor structure in combination with trenches in the semiconductor structure (21) formed along the current injection path (26).

5. Semiconductor laser device according to claim 3 or 4, characterized in that the ends of the current injection paths (26) facing toward the radiation-generating quantum well structure (11) exhibit a spacing of 10 - 50 μm therefrom.

6. Semiconductor laser device according to one of the claims 1 through 5, characterized in that two pump radiation sources (20) are arranged at opposite sides of the quantum well structure (1), these emitting pump radiation (2) into the quantum well structure (11) in operation.

7. Semiconductor laser device according to one of the claims 1 through 5, characterized in that a plurality of pump radiation sources (20) are arranged star-like around the quantum well structure (11), these emitting pump radiation (2) into the quantum well structure (11) in operation.

8. Semiconductor laser device according to claim 6 or 7, characterized in that respectively two pump radiation sources (20) arranged at opposite sides of the quantum well structure (11) together form a laser structure for the optical pumping by means of laser emission.

9. Semiconductor laser device according to one of the claims 1 through 8, characterized in that the edge-emitting semiconductor structure (21) comprises at least one active layer (25) embedded between a first (23) and a second (24) waveguide layer that are in turn embedded between a first (28) and a second (29) cladding layer.

10. Semiconductor laser device according to claim 9, characterized in that the boundary surface between edge-emitting semiconductor structure (21) and quantum well structure (11) is at least partially reflective.

11. Semiconductor laser device according to one of the claims 1 through 10, characterized in that the edge-emitting semiconductor structure (21) comprises a plurality of active layers (25) that are connected in series by means of tunnel transitions, and the quantum well structure comprises a plurality of quantum well groups that respectively lie at the height of an active layer (25) of the edge-emitting semiconductor structure (21).

12. Semiconductor laser device according to claim 1, characterized in that the radiation-emitting quantum well structure (11) and the pump radiation source (20) are arranged above one another on the substrate (1), and in that the quantum well structure (11) is optically coupled to the edge-emitting semiconductor structure (21), so that pump radiation (2) is guided into the quantum well structure (11) in the operation of the semiconductor laser device.

13. Semiconductor laser device according to claim 12, characterized in that

the edge-emitting semiconductor structure (21) comprises a first waveguide layer (23) and a second waveguide layer (24) (downstream as seen from the substrate (1)) between which an active layer (25) is arranged; and in that the quantum well structure (11) is epitaxially grown on the second waveguide layer (24), covers only a sub-region of the edge-emitting semiconductor structure (21) and is optically coupled thereto, so that at least a part of the pump radiation (2) generated in the edge-emitting semiconductor structure (21) is guided into the quantum well structure (11).

14. Semiconductor laser device according to claim 13,
characterized in that
at least one gain-guided radiation-emitting active region that serves as pump radiation source (20) is formed in the edge-emitting semiconductor structure (21) by means of at least one correspondingly structured current injection path (26) on the surface of the second waveguide layer (24).

15. Semiconductor laser device according to claim 13,
characterized in that
at least one gain-guided [sic] radiation-emitting active region that serves as pump radiation source (20) is formed in the edge-emitting semiconductor structure (21) by means of at least one correspondingly structured current injection path (26) on the surface of the second waveguide layer (24) in combination with correspondingly etched trenches in the second waveguide layer (24).

16. Semiconductor laser device according to one of the claims 13 through 15,
characterized in that
the refractive index of the second waveguide layer (24) is higher than the refractive index of the first waveguide layer (23).

17. Semiconductor laser device according to one of the claims 13 through 15,

characterized in that
the active layer (25) is asymmetrically placed in the waveguide formed by the two waveguide layers (23, 24).

18. Semiconductor laser device according to one of the claims 2 through 17, characterized in that
the substrate (1) is composed of a material that is transmissive for the laser beam (5) generated in he semiconductor laser device; and in that
a resonator mirror layer (3), in particular a Bragg reflector, with an optimally high reflection coefficient is applied on that side of the quantum well structure (11) facing away from the substrate (1).

19 . Method for manufacturing an optically pumped surface-emitting semiconductor laser device that comprises the following method steps:

a) applying a surface-emitting semiconductor laser layer sequence (14) with at least one quantum well structure (11) onto a substrate (1);

b) removing the surface-emitting semiconductor laser layer sequence (14) outside the intended laser region (15);

c) applying an edge-emitting semiconductor layer sequence (27) onto that region over the substrate (1) uncovered by the removal of the first semiconductor layer sequence (14), said edge-emitting semiconductor layer sequence (27) being suitable for transmitting pump radiation (2) into the quantum well structure (11); and

d) forming at least one current injection path (26) in the edge-emitting semiconductor layer sequence (27).

20. Method according to claim 19, in that the steps a through c comprise the following individual steps:

aa) applying a buffer layer (6) onto the substrate (1);

ab) applying a first confinement layer (12) onto the buffer layer (6);

ac) applying a quantum well structure (11) suited for a surface-emitting semiconductor laser onto the first confinement layer (12);

ad) applying a second confinement layer (13) onto the quantum well structure (11);

ba) removing the confinement layers (12, 13) and the quantum well structure (11) and, partially, the buffer layer (6) outside the intended surface-emitting laser region (15);

ca) successively applying a first cladding layer (28), a first waveguide layer (23), an active layer (25), a second waveguide layer (24) and a second cladding layer (29) onto the uncovered region of the buffer layer (6), whereby the respective layer thickness is designed such that the pump radiation (2) generated in the active layer proceeds into the quantum well structure (11).

21. Method for manufacturing an optically pumped surface-emitting semiconductor laser device that comprises the following method steps:

a) applying an edge-emitting semiconductor layer sequence (27) onto a substrate (1);

b) applying a surface-emitting semiconductor laser layer sequence (14) with at least one quantum well structure (11) onto the edge-emitting semiconductor layer sequence (27);

c) removing the surface-emitting semiconductor laser layer sequence (14) outside the intended laser region (15); and

d) forming at least one current injection path (26) in the edge-emitting semiconductor layer sequence (27).

22. Method according to claim 21, in that the steps a) through c) comprise the following individual steps:

aa) applying a buffer layer (6) onto the substrate (1);

ab) successively applying a first waveguide layer (23), an active layer (25) and a second waveguide layer (24) onto the buffer layer (6);

ba) applying a first confinement layer (12) onto the second waveguide layer (24);

bb) applying a quantum well structure (11) suited for a surface-emitting semiconductor laser onto the first confinement layer (12);

bc) applying a second confinement layer (13) onto the quantum well structure (11);

ca) removing the confinement layers (12, 13) and the quantum well structure (11) and, partially, the second waveguide layer (24) outside the intended surface-emitting laser region (15).

Abstract

Optically pumped, surface-emitting semiconductor laser device and method for its manufacture

The invention concerns an optically pumped surface-emitting semiconductor laser device with at least one radiation-generating quantum well structure (11) and at least one pump radiation source (20) for optically pumping the quantum well structure (11), in which the pump radiation source (20) comprises an edge-emitting semiconductor structure (21). The radiation-generating quantum well structure (11) and the edge-emitting semiconductor structure (21) are epidaxially [sic] grown on a common substrate (1). A very effective and homogenous optical pumping of the radiation-generating quantum well structure is advantageously possible with this monolithically produced semiconductor laser device. Furthermore, methods for manufacturing inventive semiconductor laser devices are specified.

Figure 1

Reference list

1	substrate
2	pump radiation
3	first resonator mirror
4	second resonator mirror
5	laser beam
6	buffer layer
7	electrically insulating mask layer
8	exit window
9	n-contact layer
10	surface-emitting laser structure
11	quantum well structure
12	first confinement layer
13	second confinement layer
14	surface-emitting semiconductor laser layer sequence
15	laser region
16	principal face
17	etching mask
18	absorber layers
20	pump radiation source
21	edge-emitting semiconductor structure
22	radiation-emitting region
23	first waveguide layer
24	second waveguide layer
25	active layer
26	current injection path
27	semiconductor layer sequence
28	first cladding layer
29	second cladding layer
30	contact layer

31	end mirror
32	p-contact layer
33	mirror
34	deflection mirror
35	frequency-selective element
36	frequency doubler